PROTECTION OF THE LOWER EXTREMITIES IN TWO AND THREE WHEELERS WITH SAFETY CELL

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ABSTRACT

Drivers of motorbikes or scooters have previously been unable to take advantage of new features in passive safety. However, new motorbike and scooter designs with safety cells and restraint systems keep the driver inside the vehicle during an accident and afford protection from serious injuries.

While head and upper body are well protected in this kind of vehicle, there is still the risk of injuries to the extremities. Specially designed knee-cushions keep the lower legs inside the safety compartment in a side impact or if the vehicle overturns, which improves the protection of the lower extremities, but the upright seating position still leads to high loads on the pelvis and femurs during a frontal impact.

Using numerical and experimental simulations, this study shows that a knee airbag in combination with a knee-cushion clearly reduces the loads on the pelvis and femurs during a frontal impact situation.

INTRODUCTION

While the occupants of motor vehicles are now protected increasingly from serious injury in the event of an accident by a variety of safety features, the drivers of motorised two-wheelers have remained particularly vulnerable.

A new class of vehicles, motor scooters with a safety compartment (e. g. BMW C1), is intended to provide the user with a level of safety comparable to modern small cars.

Because of the upright seating position and the different dimensions of the safety cell, the demands on the restraint and protection systems, particularly regarding the lower extremities, differ from those for cars.

The basis for all the investigations has been the prototype of a new type of motor scooter. A requirement for the protection systems investigated in this study was that they could be installed without major structural measures.

VEHICLE CONCEPT

Within the framework of the EU project BRPR-CT97-0496, an innovative city vehicle (Figure 1.) the so-called Zero Emission Downsized Improved Safety urban vehicle (ZEDIS) was developed with the participation of PIAGGIO Veicoli Europei S.p.A., Centro Ricerche FIAT, Hydro Raufoss Automotive, BREED UK Ltd., University of Bath, and the Technical University Berlin.

Figure 1. ZEDIS prototype.

The a three-wheeled motor scooter has a rigid safety compartment with a frontal crumpling zone. Intrusion of the front wheel into the foot space is avoided by a special framework construction. In order to reduce the forces on the upper legs in the event of a frontal collision, knee-cushions are employed consisting in the prototype of foam plastic approx. 80 mm thick.

The driver wears a conventional three-point safety belt together with an additional diagonal belt, which is necessary since a three point belt would only be able to restrain the upper torso in the event of a side-ways fall in one direction. Both belt systems are fitted with pretensioners and force limiters.

The vehicle is intended to be used in towns and cities, and the electric-drive allows a maximum speed of 50 km/h.

ACCIDENT ANALYSIS

The three-wheeled ZEDIS is basically similar in use and driving dynamics to motor scooters and motor-bikes, and the accident conditions and configurations can be expected to be similar. In view of its safety features, however, the injury mechanisms of the ZEDIS driver will more resemble those of car occupants.

Various studies [5, 6] show that the majority of accidents involving two-wheelers are collisions with cars, more than 50% of which are frontal.

In-depth surveys of the Medizinische Hochschule Hannover [5] show that for 95% of registered accidents involving motor scooters, the relative speed did not exceed 50 km/h. In a collision with an average car this would lead to a change of velocity Δv for the ZEDIS vehicle of approximately 40 km/h.

To examine the safety system in a frontal collision, a rigid barrier collision at about 40 km/h is sufficient. This configuration was used in the sled tests of this study.

## KINEMATICS OF THE ZEDIS OCCUPANT IN A FRONTAL COLLISION

The seating position in the ZEDIS is relatively upright, due to the dimensions of the safety compartment. The lower leg is at right angles to the upper leg.

Figure 2. shows the movement of an occupant in a car crash compared to a crash of the ZEDIS. For purposes of comparison, a three-point safety-belt was used in both cases, with the same deceleration pulse. The knee-cushions had the same stiffness.

The legs of the car passenger support the lower torso throughout the forward movement of the body, and the pelvis rotates around its transverse axis. This pelvic rotation reduces the translational pelvic deceleration, but there is also an increased danger that the lap belt can slide up to the abdomen.

In the ZEDIS, the unimpeded linear forward movement of the occupant is ended after approximately 60 ms when the upper legs impact at right angles into the knee-cushion. The lower legs have very little influence on the movement of the lower torso.

CAR   ZEDIS
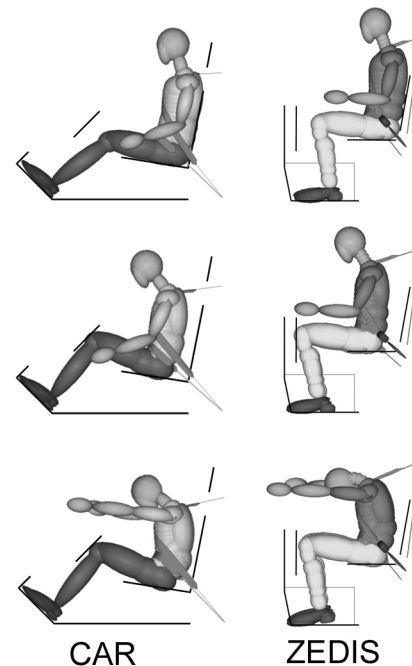
Figure 2. Kinematic comparison between car and ZEDIS.

The impulse experienced by the occupant on hitting the knee-cushion is transmitted directly to the pelvis, which rotates very little around its transverse axis.

The trajectories and the resultant decelerations of the head and upper torso of the ZEDIS occupant differ very little from those of a car occupant. The main differences between the two seating positions are the movement of the lower torso and the loads on the lower part of the body. The pelvis of the car occupants moves further forward during a collision than that of a ZEDIS driver.

The maximum forward displacement of the pelvis in the ZEDIS vehicle is determined by the position of the knee-cushion. The pelvic deceleration was much higher than for car occupants.

The upright seating position and the relatively compact safety cell of the ZEDIS vehicle mean that the loads on the pelvis and the femur are greater than for the same cell deceleration in a car.

Simulations and tests show that both the feet and the tibia are only subjected to relatively low loads. Forces typically acting on the tibia in a car crash are generally not observed for the ZEDIS.

INJURY MECHANISMS

The occupants of a car are used as a reference for the causes and patterns of physical injury, in particular to the lower extremities.

Foot and ankle injuries due to intrusions should not be a problem in frontal collisions of the ZEDIS vehicle due to the frame construction, which prevents intrusions into the footwell.

Abdomen and pelvis

Abdominal injuries to car occupants are caused primarily by intrusions and compressions. The ZEDIS is designed to eliminate the danger of intruding vehicle components.
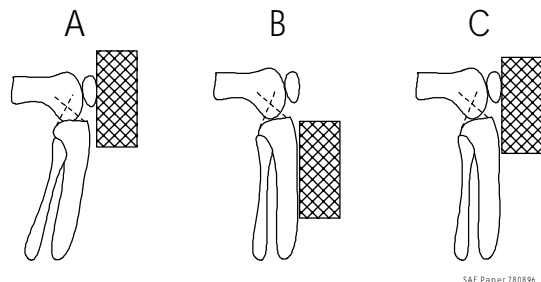
In frontal collisions, the forces are generally transmitted along the femur to the pelvic area. However, the patella and femur are damaged at a much lower level of force than that required to fracture the pelvis [4]. A pelvic fracture is therefore unlikely.

Investigations by Kramer [3] show that the rotation of the pelvis about the transverse axis can be taken as an indicator of the risk of injury to the pelvis and abdomen. With angles of rotation up to about 24°, it is possible to withstand a peak deceleration of up to 80 g for 3 ms. For larger angles of rotation, the maximum deceleration is reduced to about 13 g for 3 ms, due to the phenomenon of submarining. Decelerations above 13 g and 80 g respectively lead to abdominal and pelvic injuries.

It is generally assumed that decelerations of the pelvis of 60 - 80 g over 3 ms can be withstood without injury, as long as there is no submarining.

Femur and knee

Viano [7] has shown that a force acting directly on the patella and passing along the femur (Position A, Figure 3.) presents only a limited threat of injury to the knee and upper leg.

Figure 3. Typical types of knee contact in frontal collisions [7].

Less direct impacts, such as those shown in Positions B and C (Figure 3.), pose a greater risk of injury to the knee. The forces are transmitted to the upper leg in part through the tibia and the cruciate ligaments. This can lead to the knee collapsing, even in the event of minor displacements and small forces.

Atkinson [1, 2] has shown that not only the forces involved but also the size of the contact area have a considerable effect on the resultant injuries.

A large area of impact at the knee leads to a reduction of the risk of injury for this region. A point force, on the other hand, can lead to a fracture of the patella.

OPTIMISING KNEE-CUSHIONS FOR FRONTAL COLLISIONS

Requirements

In the event of a frontal collision, the knee-cushions have the primary function of using the unavoidable contact between the legs and the interior of the vehicle to reduce the kinetic energy of the person in the vehicle.

The decisive parameters for protective effect of the restraints are the distance to the knee, the shape, and the selected contact points on the leg. The knee-cushions should be positioned so that the main forces are exerted axially along the femur. The shape of the cushion should prevent the femur from sliding downwards, since this would increase the loads acting on the tibia.

The stiffness of the cushion material has a considerable effect on the risk of injury to the knee, upper leg and pelvic area. Layered materials providing gradually increasing levels of stiffness can offer better protection for accidents of varying severity and for occupants of various sizes than a cushion with an homogeneous response. The stiffness must be chosen so that even in the event of severe accidents with large passengers the compaction limit is not reached.

The top layer of the cushion should be relatively soft, so that in the event of light bumps there is no painful contact.

Variant 1: Thick cushion

The cushion is as thick as possible while still allowing sufficient leg space for a large occupant, for example the 95th-percentile male.

The knee-cushion originally used in the ZEDIS prototype was 80 mm thick in the contact area. It was increased to 120 mm and still allowed leg space for the 95th-percentile male.

As in the ZEDIS prototype and the sled tests, NORYL EF 100 was used as cushion material in order to assess the effects of earlier contact on the movements of the occupant and the forces acting on them.

Variant 2: Thick soft cushion

In this variant, a 120 mm cushion was again used, but in this case with gradually increased levels of stiffness. However, even the hardest layer was softer than the material used in Variant 1.

If the cushion is thicker, then a softer material can be used. This reduces the forces acting on the knee and the upper leg in the event of an impact.

The material characteristics were chosen so that the deformation path for a 95th-percentile male would be as near as possible to 120 mm.

Variant 3: Knee airbag

Active restraints or knee airbags offer the same advantages as a thick cushion, but they are only employed in the case of a collision. This means that there is more leg space the rest of the time.

In this investigation, knee airbag systems are used in preference to active restraints or knee airbags with load distribution, since they have a simpler construction yet offer similar protection.

The airbags used had a volume of about 5 litres, operated by inflators from standard side airbags.

In order to be able to exclude the effects of unfolding in this primary investigation, the airbags were initially unfolded, both in the tests and also in the simulation. The two airbags are deployed downwards, so that the knees were not hit directly by the expanding bag.

Behind the airbags, 80 mm cushion blocks were mounted to avoid any knee contact with rigid structures if the restraining potential of the airbag is exceeded.

This combination of airbag and conventional cushion also offers the additional advantage that only relatively small airbags are necessary to fill the space between the knee and the structure behind the airbag. Larger volumes mean a more powerful inflator is needed, and this can increase risks to occupants who are out of position.

NUMERICAL MODELLING OF THE KNEE-CUSHION

Using a MADYMO model, the three knee-cushion variants were investigated under varying conditions.

Simulation model

Various drop weight tests were carried out to determine the deformation characteristics of the materials used, and four sled tests supplied the necessary data for the validation of the model.

The simulation model generally corresponded well to the sled tests. However, the validation of the model showed that the femur-forces in the simulation were consistently higher in the simulation than in the sled tests. This must be taken into account when interpreting the results of the simulation.

Figure 4. shows the sled deceleration during the tests and the simulation. The change in velocity was 40.3 km/h.
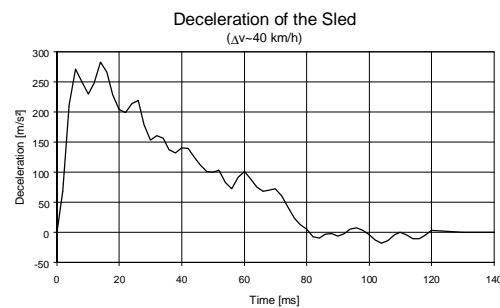
Figure 4. Sled deceleration used in test and simulation.

Simulation results

The simulation results show that the knee-cushions originally proposed for the ZEDIS prototype do not offer satisfactory protection for pelvis and legs.

Variant 1: Thick cushion

Earlier contact with the cushion is not in itself sufficient to appreciably reduce the loads on the pelvis and the lower extremities. Table 1. shows that the pelvis deceleration is still critical, and the femur force is at the critical limit. Because the cushion material is so stiff, the deformation is not as large as it could be.

The knee-cushion only has a slight influence on the deceleration of the head and chest.

Variant 2: Thick soft cushion

A soft cushion clearly reduces the loads on the lower extremities and the pelvis (Table 1.).

Table 1.
**Results for three types of knee-cushion**

	Prototype (sled test)	Variant 1	Variant 2
a_{3ms}-head	33.3 g	33.8 g	36.6 g
a_{3ms}-chest	49.9 g	45.0 g	42.7 g
a_{3ms}-pelvis	89.1 g	84.8 g	49.2 g
femur force	9078 N	9978 N	3098 N
tibia compression force	1342 N	1152 N	701 N
tibia index	0.630	0.554	0.394
cushion deformation	24 mm	27 mm	70 mm

The considerably larger deformation of the cushion could be used to reduce the kinetic energy of the occupant at a moderate force level. Nevertheless, a cushion that is 120 mm thick offers sufficient reserves to restrain even heavier people.

Variant 3 (Knee airbag)

The side airbag model on which the simulation was based was very similar in terms of bag size and apertures to the components later used in the tests. It was therefore not deemed necessary to go through an extensive validation procedure for the airbag model, even though this led to certain deviations between the test and simulation.

Figure 5. shows the simulation of the occupant at different time steps.

0 ms   25 ms   65 ms
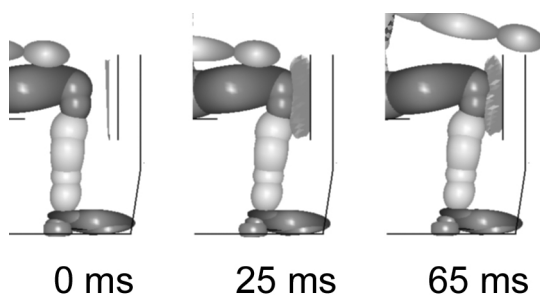
Figure 5. Knee airbag in the simulation.

The tendency in the simulation was for the loads on the occupant to be lower when the airbags were inflated sooner. However, the sensor technology determines the earliest possible time-point for triggering inflation. Crash tests with the ZEDIS prototype showed that the very stiff safety compartment provides good signals for the early triggering of the airbag.

Table 2. shows a comparison of the results for various triggering times in comparison with the values for the prototype.

Table 2.
The results for various airbag activation times

	12 ms	17 ms	22 ms
a_{3ms}-head	36.9 g	34.6 g	33.0 g
a_{3ms}-chest	37.3 g	39.0 g	45.1 g
a_{3ms}-pelvis	46.1 g	67.0 g	81.7 g
femur force	5305 N	7763 N	9260 N
tibia compression force	893 N	928 N	768 N
tibia index	0.253	0.400	0.623

When there is a longer period between an impact and the activation of the airbag system, the knee will be closer to the cushion, providing less space for the airbag to inflate. However, since the same amount of gas is produced, the result is that the maximum pressure of the gas will be slightly higher for the later activation.

If the pressure in the airbag is too low, there is a danger that the knees will fully compress the airbag and hit the cushion, reducing the restraining effect.

KNEE AIRBAG TEST

In comparison with the other two options tested (thick cushion, thick soft cushion), the knee airbags offered the best protection, and were therefore subjected to a component analysis. The test was intended to show whether the low values obtained in the simulation model corresponded to reality.

The airbag test was carried out using fixed three-point seat belts without pre-tensioner or force limiter, so that the values measured on the crash dummy would be higher than the results from the simulation and the other sled tests. Therefore an additional reference test was carried out with this simplified belt system and the knee-cushion from the prototype.

Test set-up

For the test, thorax/pelvis side airbags were used from a compact-class car, and were modified to function as knee airbags.

The size of the airbag was reduced to 230 mm x 300 mm by adding two additional seams

(Figure 6.). Since the same amount of gas was produced this had the effect of increasing the internal pressure in the airbag to the necessary level. The vent on the airbag, which was no longer required, is in one of the unused side sections (lower right).
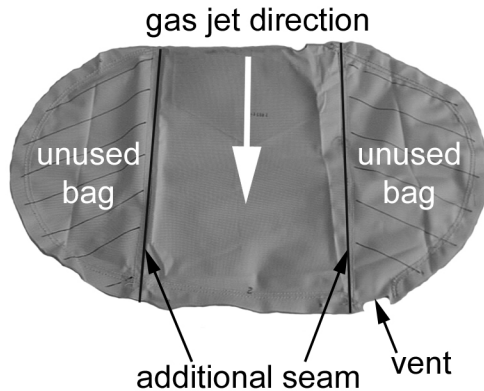

Figure 6. Modified airbag.

The redundant parts of the airbags were not cut off so that in the event that one of the seams failed the system would not cease to function completely, although the internal pressure would drop.

The material used for side airbags is not designed for the impacts involved in these tests, so that there was a risk that the airbags would burst. In order to obtain measurable results, the triggering time for the inflation of the airbags was therefore set back from 12 ms after the crash began to 17 ms. The knees then hit the airbags when they were only half inflated, and the inflator could continue to inflate an airbag even if it had begun to tear.

These factors would no longer need to be taken into consideration for purpose-built knee airbags.

Figure 7. shows the test set-up using a 50th-percentile Hybrid III dummy, which in this test was not equipped with instrumented lower legs.
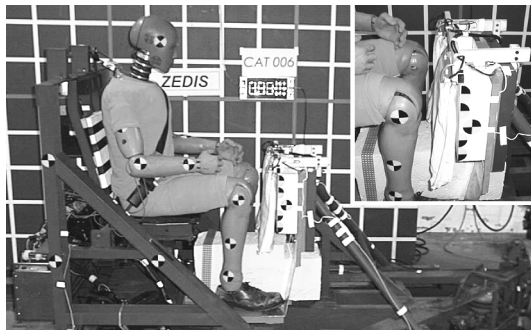
Figure 7. Test set-up with knee airbag.

Test results

Table 3. shows the results with and without airbags (three-point safety belt), and in the simulation (three-point safety belt together with an additional diagonal belt). The simplified belt system increases the injury risk of the head and chest.

Table 3.
Results with and without airbags

	Sled test no bag	Sled test 17 ms fire	Simulation 17 ms fire
a_{3ms}-head	49.9 g	51.7 g	34.6 g
a_{3ms}-chest	44.2 g	46.0 g	39.0 g
a_{3ms}-pelvis	85.7 g	57.3 g	67.0 g
femur force	5823 N	6212 N	7763 N

The knee airbag clearly reduced the loads on the pelvis. The larger forces in the femur remained below the critical level. In view of the "soft" structure of the inflated airbag, the forces are transmitted into the knee over a large area, so that the risk of injury for this part of the body should not be increased.

In the test, both airbags began to rip at the seams. An internal pressure of 2.5 to 2.8 bar was measured.

OBLIQUE COLLISIONS / FALLING OVER

The pair of rear wheels is unable to prevent the vehicle from falling sideways in the event of a frontal collision.

In addition to absorbing energy in the event of a frontal collision, the knee-cushions should also provide lateral support for the knee and lower leg and ensure that if the vehicle does fall sideways there is a cushion between the leg and the road to absorb the impact. It is necessary to find a compromise here between convenience and ease of entry on the one hand and safety on the other. The side extensions of the cushion must be chosen so that in the event of a oblique collision the legs stay inside the cushion and are not flung outwards.

In addition to protecting the legs by an outer extension of the cushion, it is also necessary to provide some protection for the legs against impacts with the central tunnel.

Simulation model

These test were based on the sled model also used in the airbag tests. In this case, however, the knee-

cushions were extended at the sides (Figure 8.) to provide additional support.
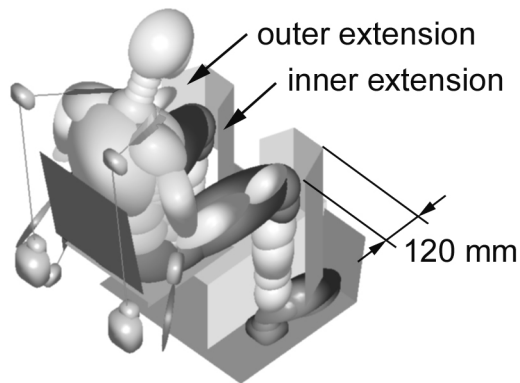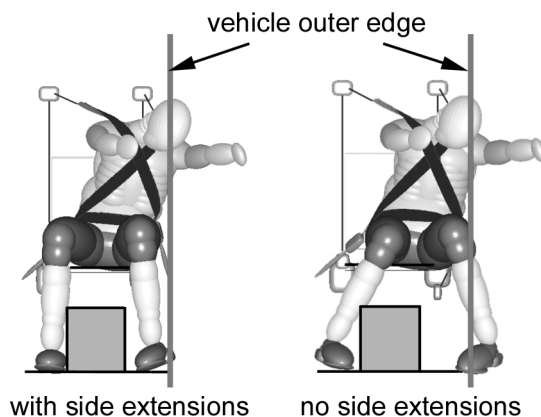

Figure 8. The knee-cushions with outer and inner extensions.

Simulation results

The deceleration applied in the model corresponded to the ZEDIS colliding with an object oblique to the left.

In Figure 9., the effects of the side extensions on the knee-cushions are depicted in comparison with the flat cushions.

Figure 9. Effects of a crash with knee-cushions with and without side extensions (knee-cushions not shown).

In the event of oblique collisions, the additional support maintains the legs in their original position. They are not forced out of the safety cell or pressed against the central tunnel. The danger that a leg could be caught between the ZEDIS and the other vehicle involved in the collision or the road surface is reduced.

In the event of a side collision with only outer extensions of the knee-cushions, it would be possible

under unfavourable circumstances for the ankle on the opposite side to be restrained by the outer cushion extension, while the thigh and knee of that leg were forced inwards, against the direction of the collision. This would result in a considerable bending moment being exerted on the lower leg.

In addition a seat shell should be used that provides the pelvis with lateral support in the event of a side collision. The central tunnel means that the sideways movement of the lower leg is restricted, and in combination with free lateral movements of the pelvis this can lead to excessive rotation of the knee and resultant ligament damage.

The modified knee-cushions lead to a pronounced rotation of the torso. Side bars are therefore essential to provide lateral support. They are also necessary to keep the head and torso inside the safety cell.

CONCLUSIONS

Numerical and experimental investigations of the loads on the lower extremities and the pelvis show that, as a result of the specific kinematics involved, the main loads are applied to the knees, thighs and pelvis, rather than the lower leg.

It has been shown to be possible, with the help of knee airbags and cushions to reduce the injury risk for the pelvis and the lower extremities. The airbag in particular offers the advantage that it only inflates in a collision, so that considerably more leg space is normally available. A cushion behind the airbag provides additional protection in severe collisions.

A special design of knee-cushion with side extensions can prevent the legs from being flung sideways out of the open-sided safety cell of the vehicle. The numerical simulations show that outer support alone for the knee and lower leg is not sufficient to protect against side collisions, since the presence of the central tunnel can lead to excessive twisting of the lower leg on the other side. In such cases it is necessary to provide side support for the pelvis as well as protection on both sides of the legs in order to prevent excessive bending loads to the lower leg.

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